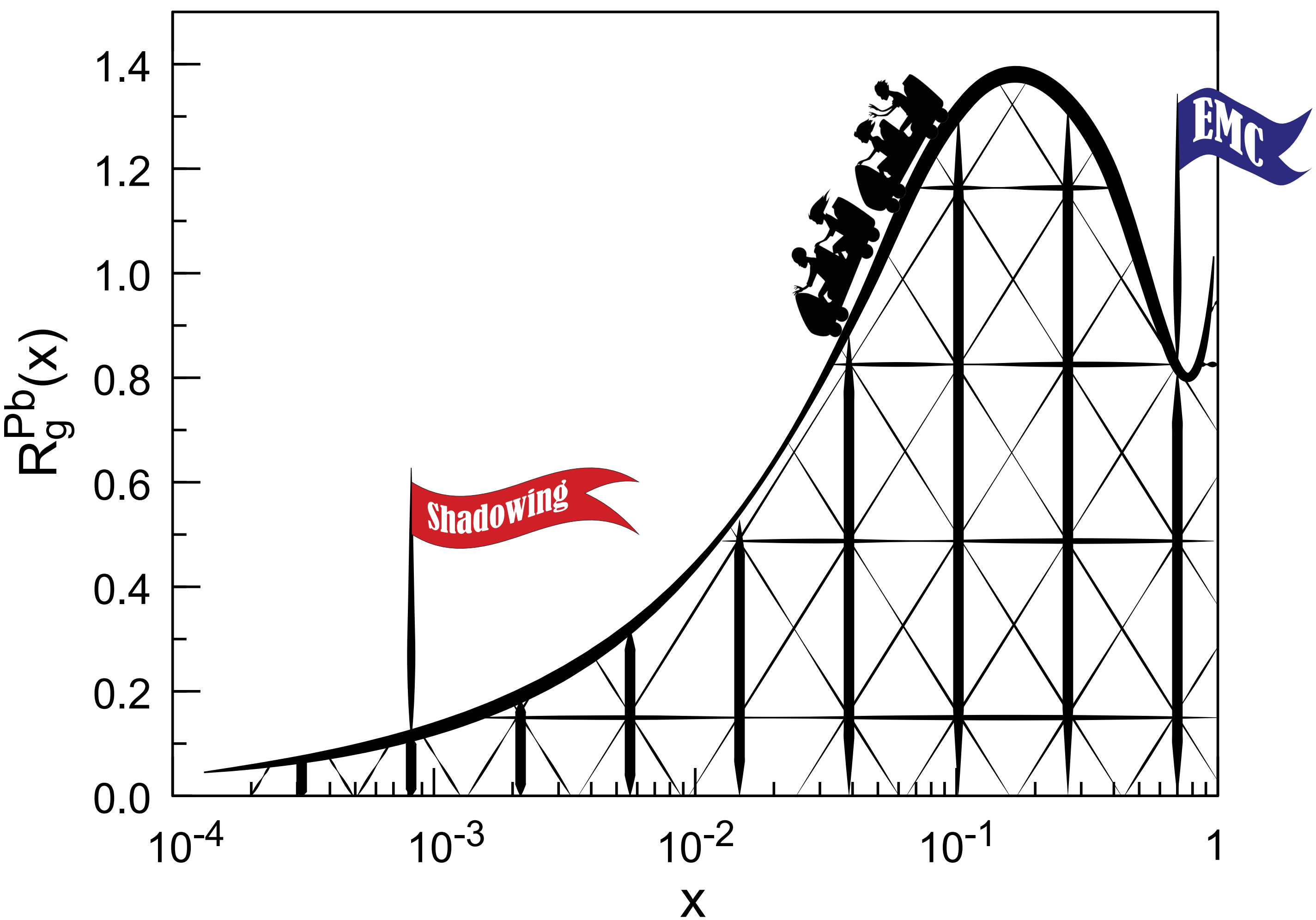
Structure Functions and Nuclear PDFs in eA Collisions



Thomas Ullrich (BNL/Yale), EIC User Group Meeting, UCB, 8/1/2016

PDF: Connecting Experiment with Theory

pp:

$$\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to b} \otimes D_{b\to o}$$

Observable

Parton Distribution Function (PDF)

Theoretical Calculations

Fragmentation Functions

Issues:

- σ_o: Experimental precision, statistics, sys. uncertainties
- $\sigma_{a\to b}$: scale uncertainties (especially for $p_T < 10$ GeV)
- $D_{b\to o}$: “black box” similar to PDFs (input from e^+e^-)

PDF: Connecting Experiment with Theory

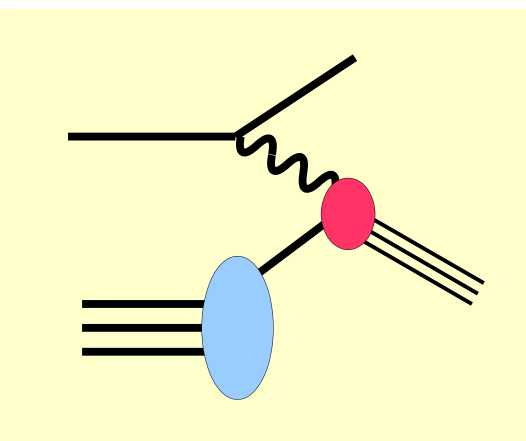
Better:

$$\sigma_o = f_{i \to a} \otimes \hat{\sigma}_{a \to o}$$

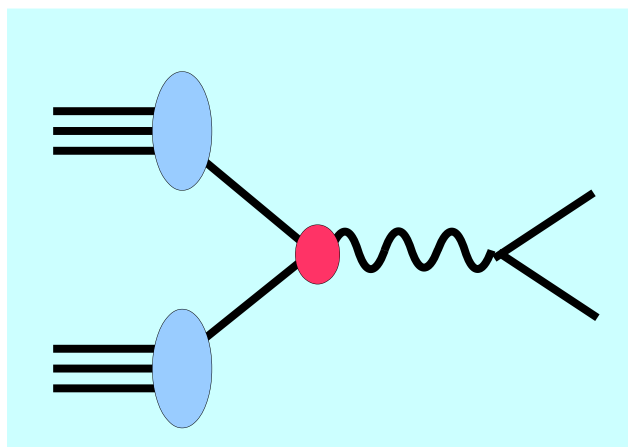
Observable

Parton Distribution Function (PDF)

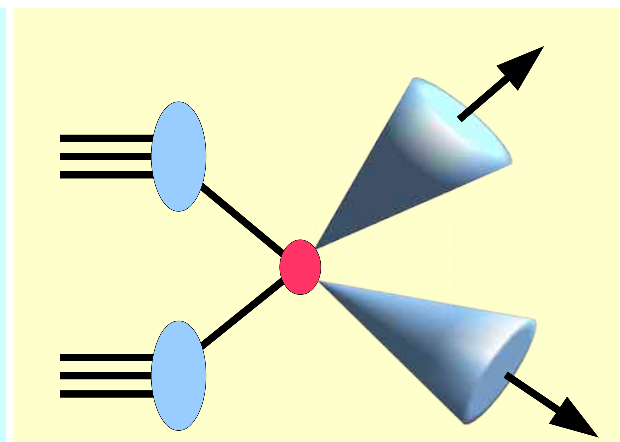
Theoretical Calculations



DIS Production

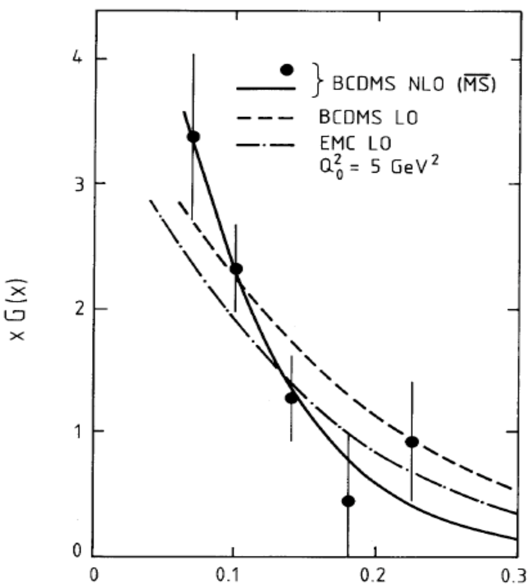


Drell-Yan

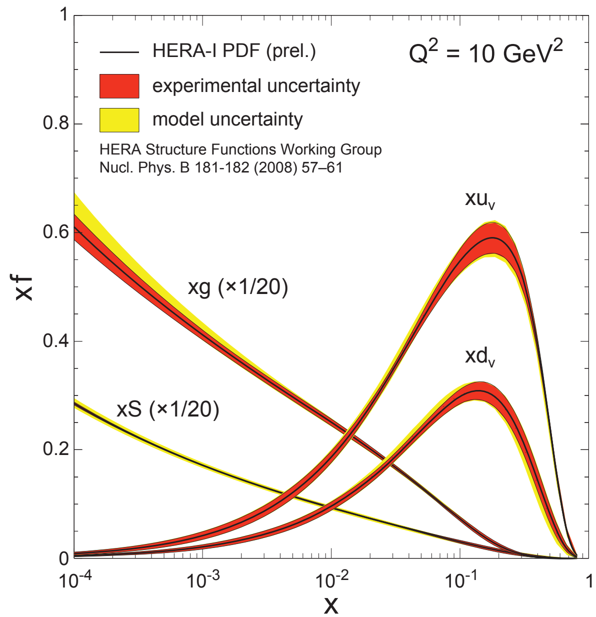


Jet Production

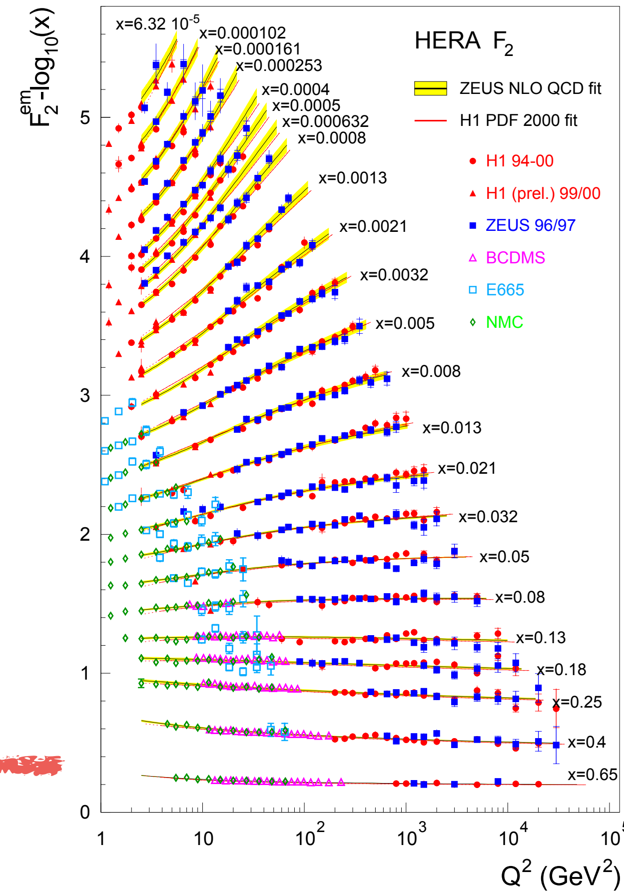
PDF (pp): Impact of Precision DIS (HERA)



CERN-EP/89-07
January 17th, 1989



2008



$\Rightarrow$
- F_2
- $dF_2/d\ln Q^2$

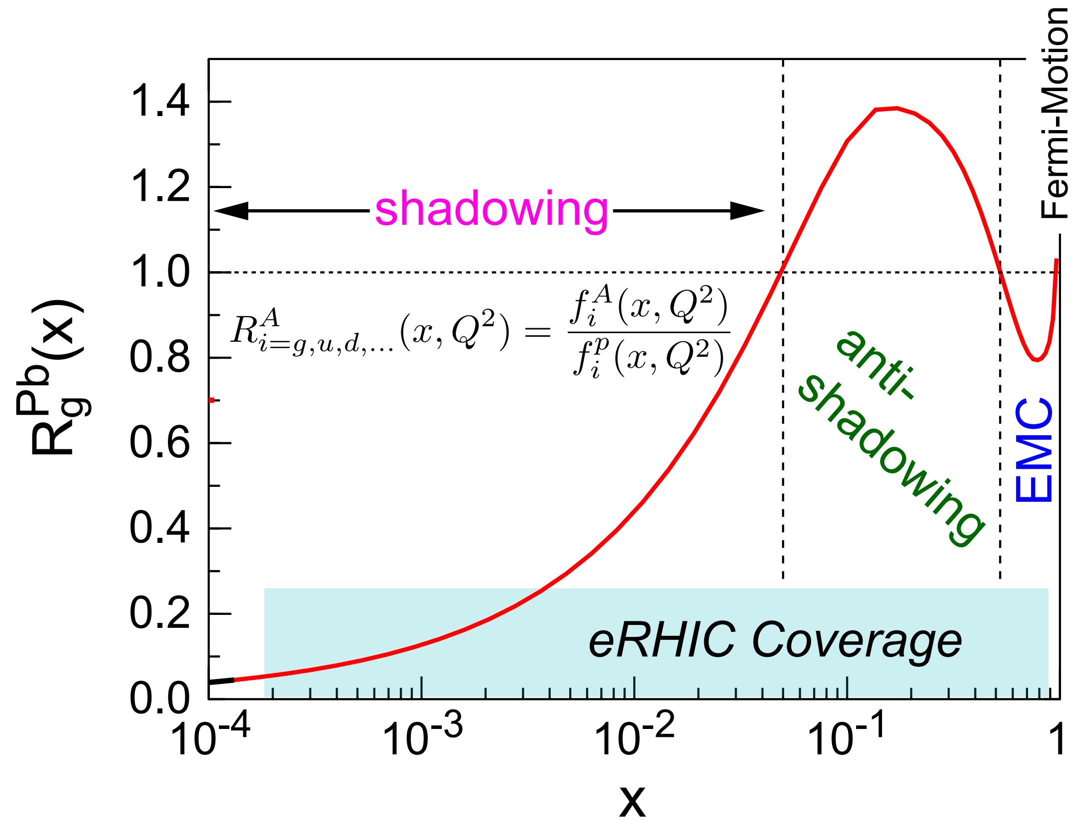
\+ pQCD+ DGLAP Evolution

$$f(x, Q_1^2) \rightarrow f(x, Q_2^2)$$

Note: Little Impact from Hera F_L measurements

Nuclear PDFs (nPDFs)

Goal: Describe <u>initial</u> state of nuclei



Issues:

- Same as in pp

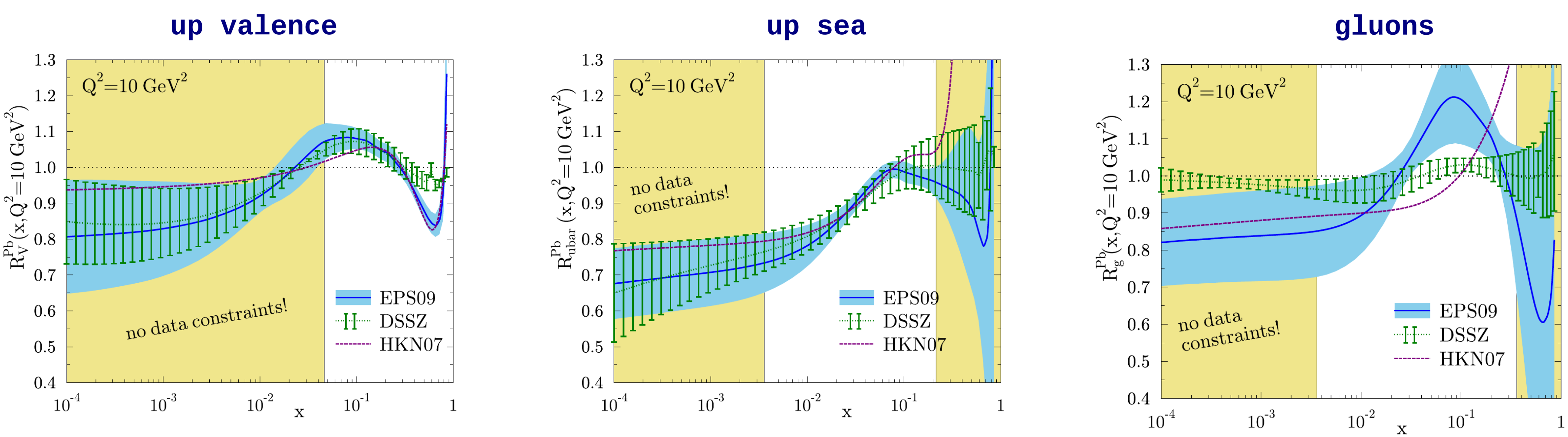
Plus

- Final state effects
- low-x: gluon saturation requires BK/JIMWLK instead of DGLA/BFKL to derive PDFs

Note: Not really an issue but rather a blessing since it will give us insight into the realm where gluon saturation effects emerge

nPDFs: Where Do We Stand?

	HKN07	EPS09	DSSZ	NCTEQ
Order in α_s	LO & NLO	LO & NLO	NLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p		✓	✓	
Neutrino-nucleus DIS			✓	
Q^2 cut in DIS	1 GeV	1.3 GeV	1 GeV	2 GeV
datapoints	1241	929	1579	708
free parameters	12	15	25	17
error analysis	✓	✓	✓	✓
error tolerance $\Delta\chi^2$	13.7	50	30	35
Free proton baseline PDFs	MRST98	CTEQ6.1	MSTW2008	CTEQ6M-like
Heavy quark treatment	ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS



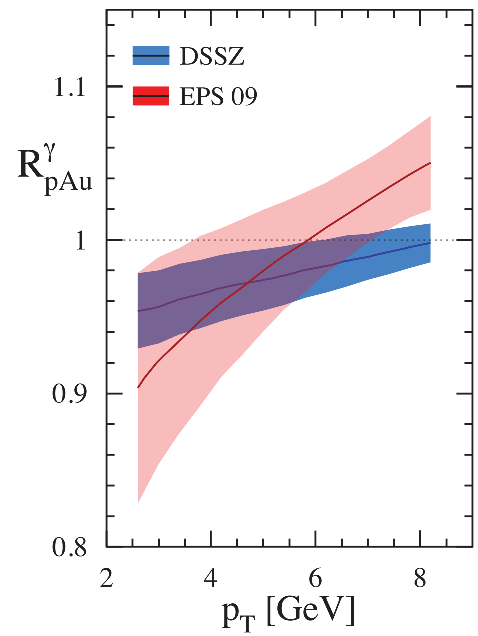
Large Differences among nPDF fits, especially for gluons

nPDFs: What Causes the Trouble?

Experiment	Process	Nuclei	Data points	χ^2 LO	χ^2 NLO	Weight	Ref.
SLAC E-139	DIS	He(4)/D	21	6.5	7.3	1	[20]
NMC 95, re.	DIS	He/D	16	14.5	15.6	5	[21]
NMC 95	DIS	Li(6)/D	15	23.6	16.8	1	[22]
NMC 95, Q^2 dep.	DIS	Li(6)/D	153	162.2	157.0	1	[22]
SLAC E-139	DIS	Be(9)/D	20	9.6	12.2	1	[20]
NMC 96	DIS	Be(9)/C	15	3.8	3.8	1	[23]
SLAC E-139	DIS	C(12)/D	7	4.1	3.2	1	[20]
NMC 95	DIS	C/D	15	15.0	13.8	1	[22]
NMC 95, Q^2 dep.	DIS	C/D	165	141.8	142.0	1	[22]
NMC 95, re.	DIS	C/D	16	19.3	20.5	1	[21]
NMC 95, re.	DIS	C/Li	20	30.3	28.4	1	[21]
FNAL-E772	DY	C/D	9	7.5	8.3	1	[24]
SLAC E-139	DIS	Al(27)/D	20	10.9	12.5	1	[20]
NMC 96	DIS	Al/C	15	6.0	5.8	1	[23]
SLAC E-139	DIS	Ca(40)/D	7	5.0	4.1	1	[20]
FNAL-E772	DY	Ca/D	9	2.9	3.4	15	[24]
NMC 95, re.	DIS	Ca/D	15	25.4	24.7	1	[21]
NMC 95, re.	DIS	Ca/Li	20	23.9	19.6	1	[21]
NMC 96	DIS	Ca/C	15	6.0	6.0	1	[23]
SLAC E-139	DIS	Fe(56)/D	26	19.1	23.9	1	[20]
FNAL-E772	DY	Fe/D	9	2.1	2.2	15	[24]
NMC 96	DIS	Fe/C	15	11.0	10.8	1	[23]
FNAL-E866	DY	Fe/Be	28	20.9	21.7	1	[25]
CERN EMC	DIS	Cu(64)/D	19	13.4	14.8	1	[26]
SLAC E-139	DIS	Ag(108)/D	7	3.8	2.9	1	[20]
NMC 96	DIS	Sn(117)/C	15	9.6	9.1	1	[23]
NMC 96, Q^2 dep.	DIS	Sn/C	144	80.2	82.8	10 (x=0.0125 only)	[27]
FNAL-E772	DY	W(184)/D	9	7.0	6.7	10	[24]
FNAL-E866	DY	W/Be	28	27.3	24.2	1	[25]
SLAC E-139	DIS	Au(197)/D	21	11.6	13.8	1	[20]
RHIC-PHENIX	π^0 prod.	dAu/pp	20	7.3	6.3	20	[28]
NMC 96	DIS	Pb/C	15	6.90	7.2	1	[23]
Total			929	738.6	731.3		

Data Sets (here EPS09)

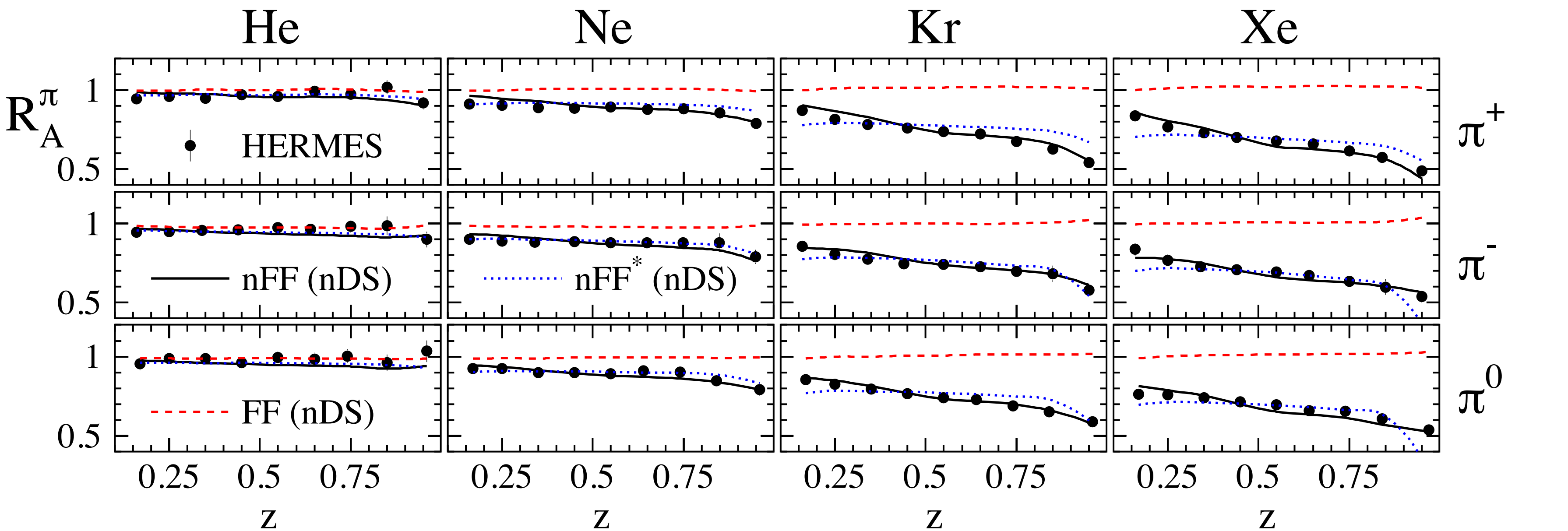
- Dominated by DIS and DY
- Exception are π^0
  - Sensitive to $g(x,Q^2)$
  - DSSZ w=1 and EPS09 w=20



From RHIC Cold QCD Plan, 2015

Prediction for direct photon R_{pA} based on DSSZ and EPS09

nPDF: Do Final State Effects Play a Role?

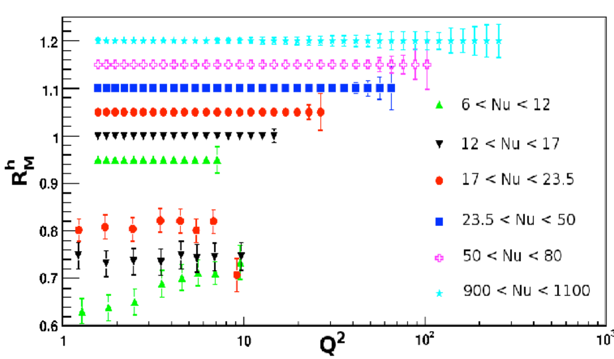


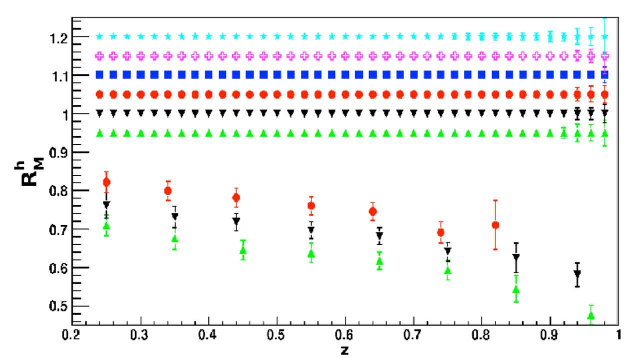
D. de Florian, R. Sassot, M. Stratmann

- nPDF and vacuum FF can **not** describe data
- Hinting we are looking at final state effects

A. Arcardi (2010)

Recall EIC's capability to measure R_{eA} as fact of Q^2, z, ν, p_T, ….



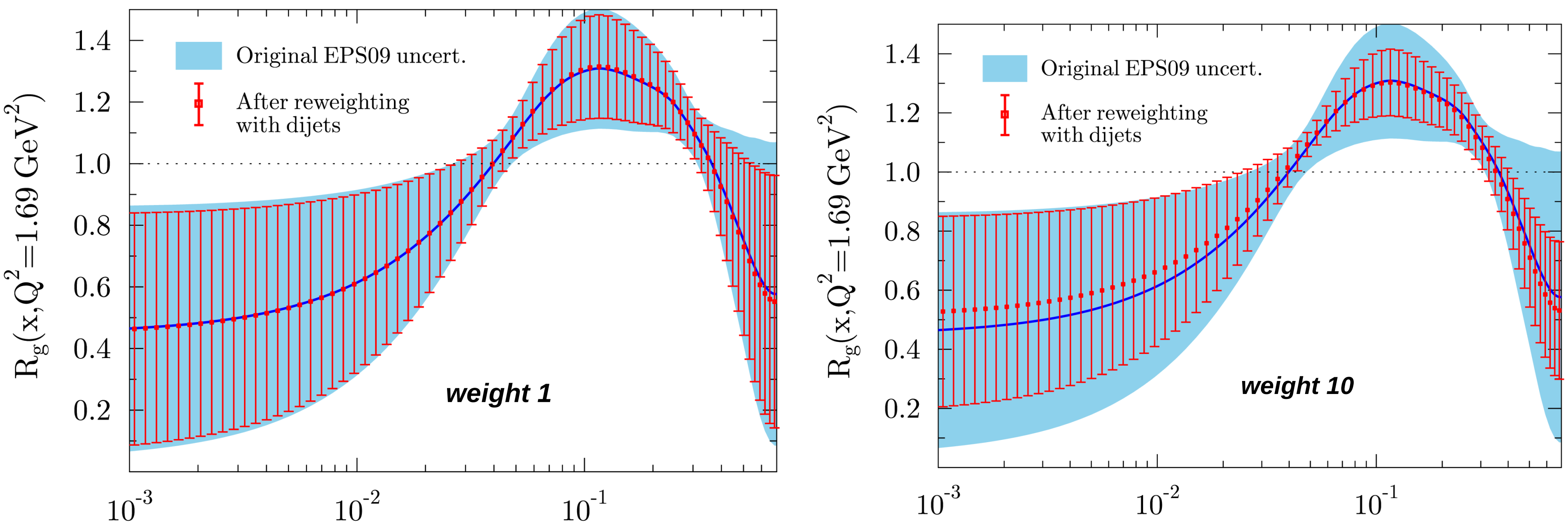


EIC

Hermes

nPDF Constraints From LHC?

- So far effect of LHC data is rather mild
- Dijets are the most constraining but focus on large Q^2 a rather “uninteresting” region
  - The (preliminary) data is completely consistent with EPS09 – would improve the large-x gluons
- EW bosons promising to relax condition $R_u=R_d$



H. Paukkunen DIS 2014

EIC: Structure Functions and nPDFs

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

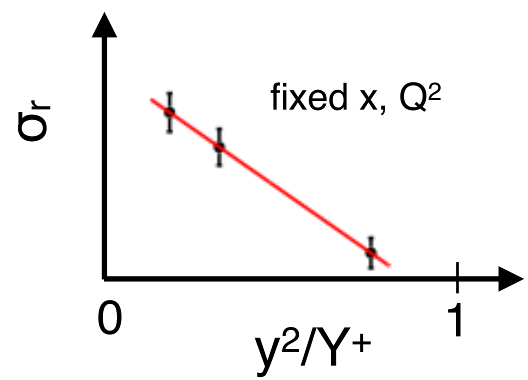
quark+anti-quark

gluon

Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dx dQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$



F_L Strategy (Rosenbluth Separation):

Recall $Q^2 = x\,y\,s$

F_L = Slope of y^2/Y_+ for different s at fixed x, Q^2

EIC Impact Study (e+A)

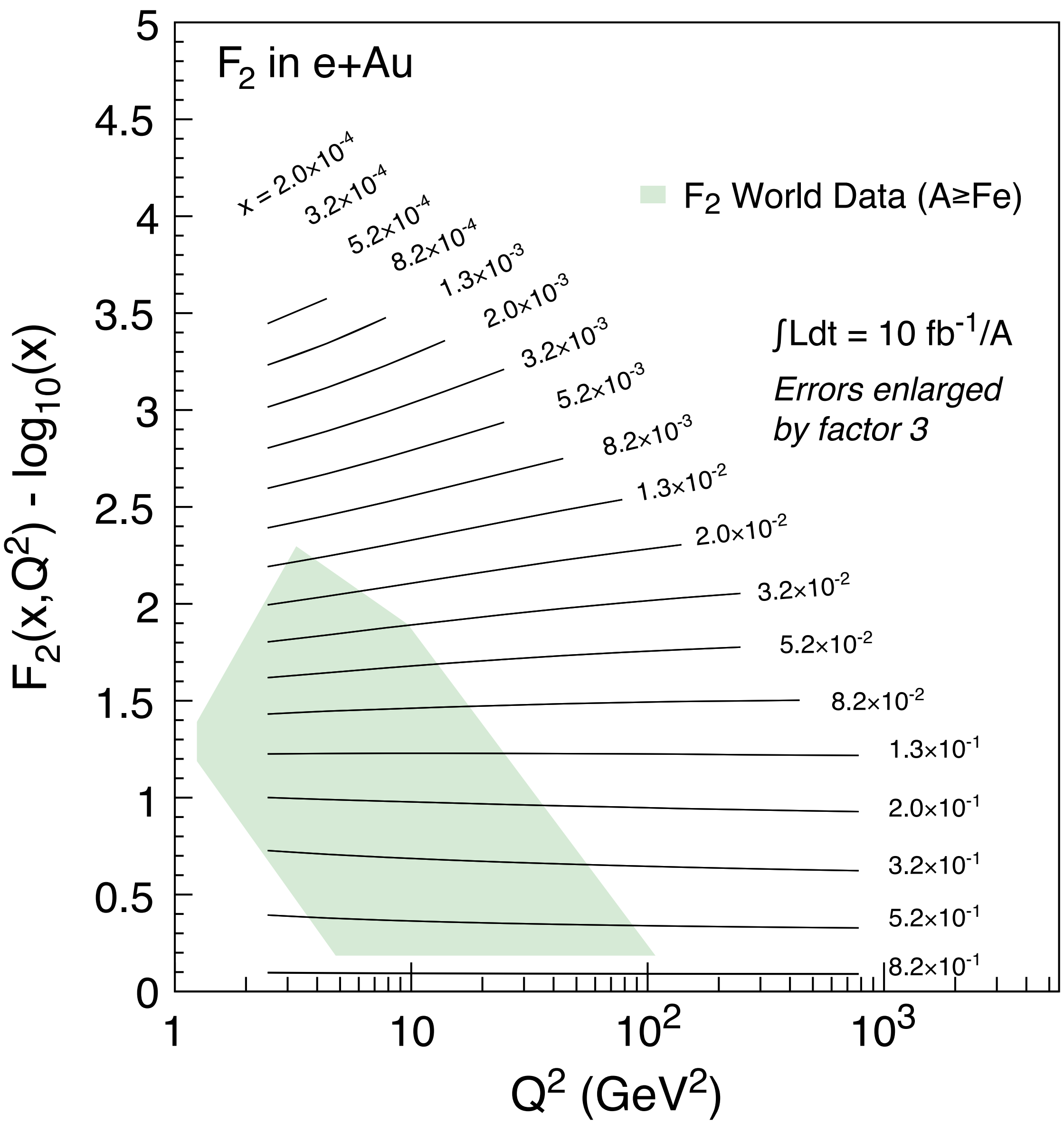
F_2

- Use Pythia6 + EPS09 to generate data
- Acceptance cuts, smearing
- Generate sufficient statistics (10^7 events) to minimize statistical fluctuations, scale errors to 10 fb^{-1}
- Statistical uncertainty is negligible
- Assume a realistic 3% systematic uncertainty (~HERA)
- Use HERMES method to calculate F_2 from σ_r

F_L

- 5 and 20x50 GeV: A $\int$Ldt = 2 fb^{-1}
- 5 and 20x75 GeV: A $\int$Ldt = 4 fb^{-1}
- 5 and 20x100 GeV: A $\int$Ldt = 4 fb^{-1}

F_2 Structure Function in e+A



- The pseudo-data is scaled to the EPS09 calculation
- Errors on pseudo-data and EPS09 are scaled for visibility
- At higher x, uncertainties on EPS09 and pseudo-data are negligible
- At smaller x, pseudo-data uncertainties are much smaller than EPS09
- Good lever arm at $x \sim 10^{-3}$
- Systematic uncertainties dominate, not $\mathcal{L}$ hungry

Data points offset for better visibility

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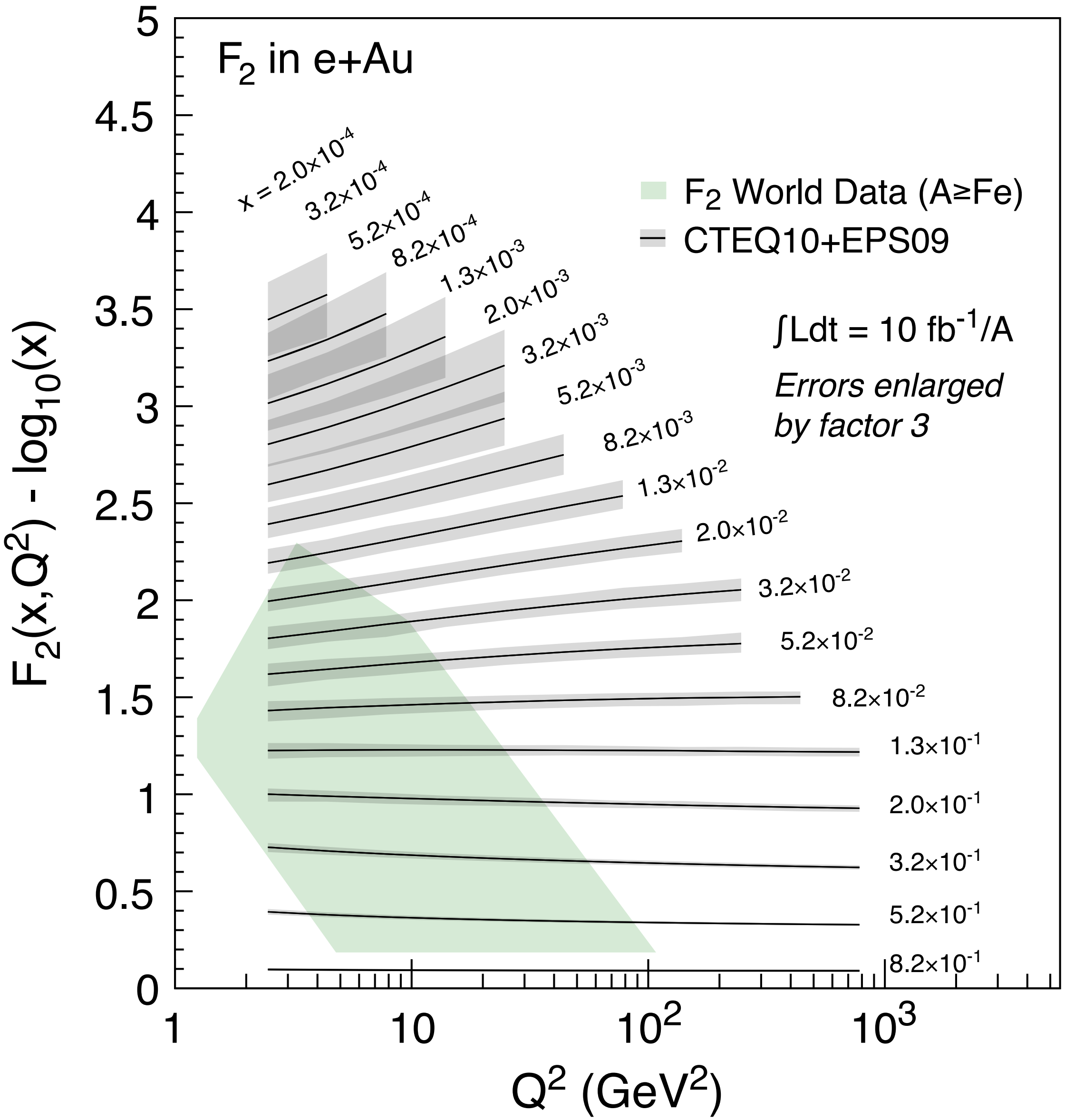

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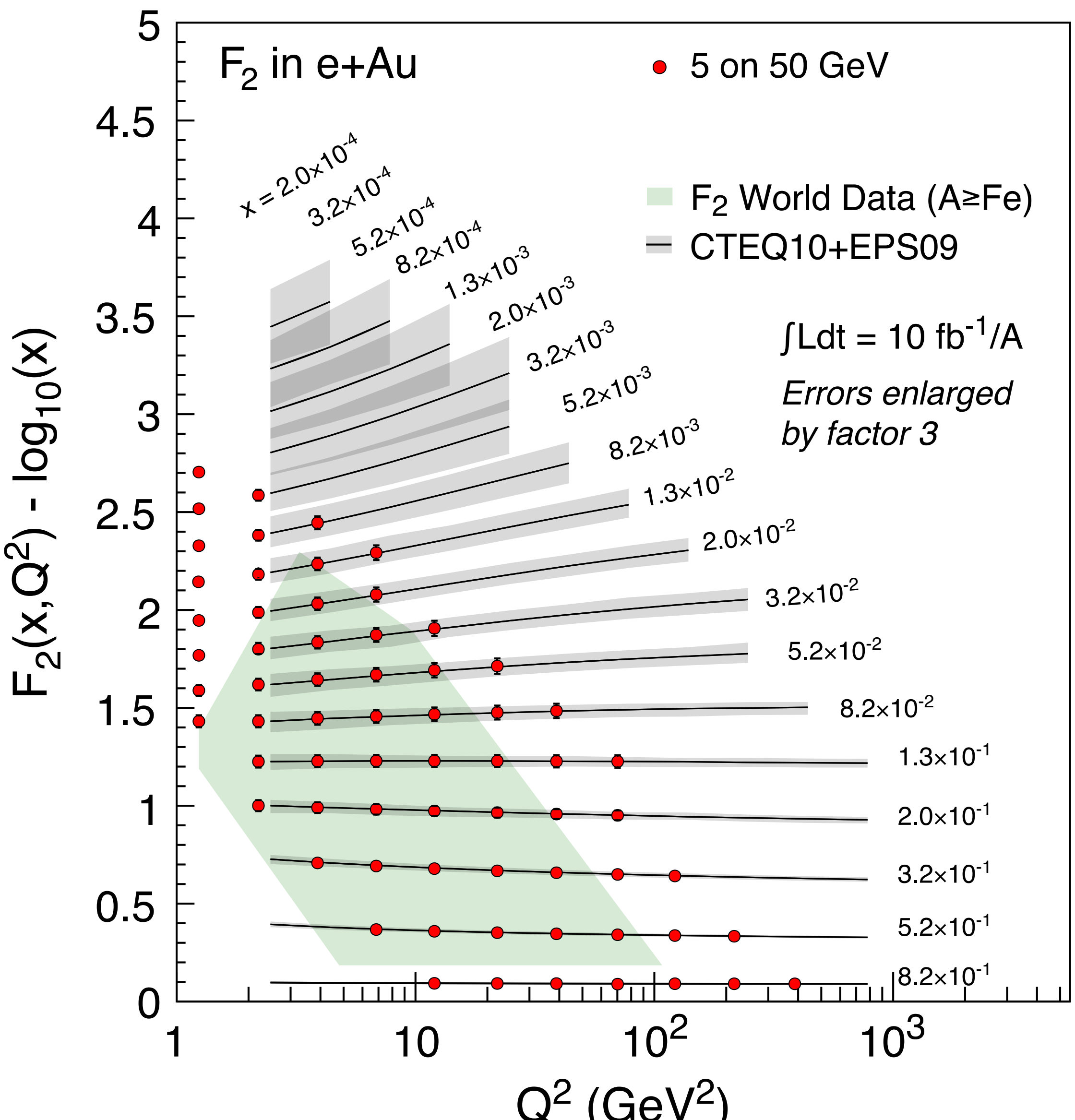

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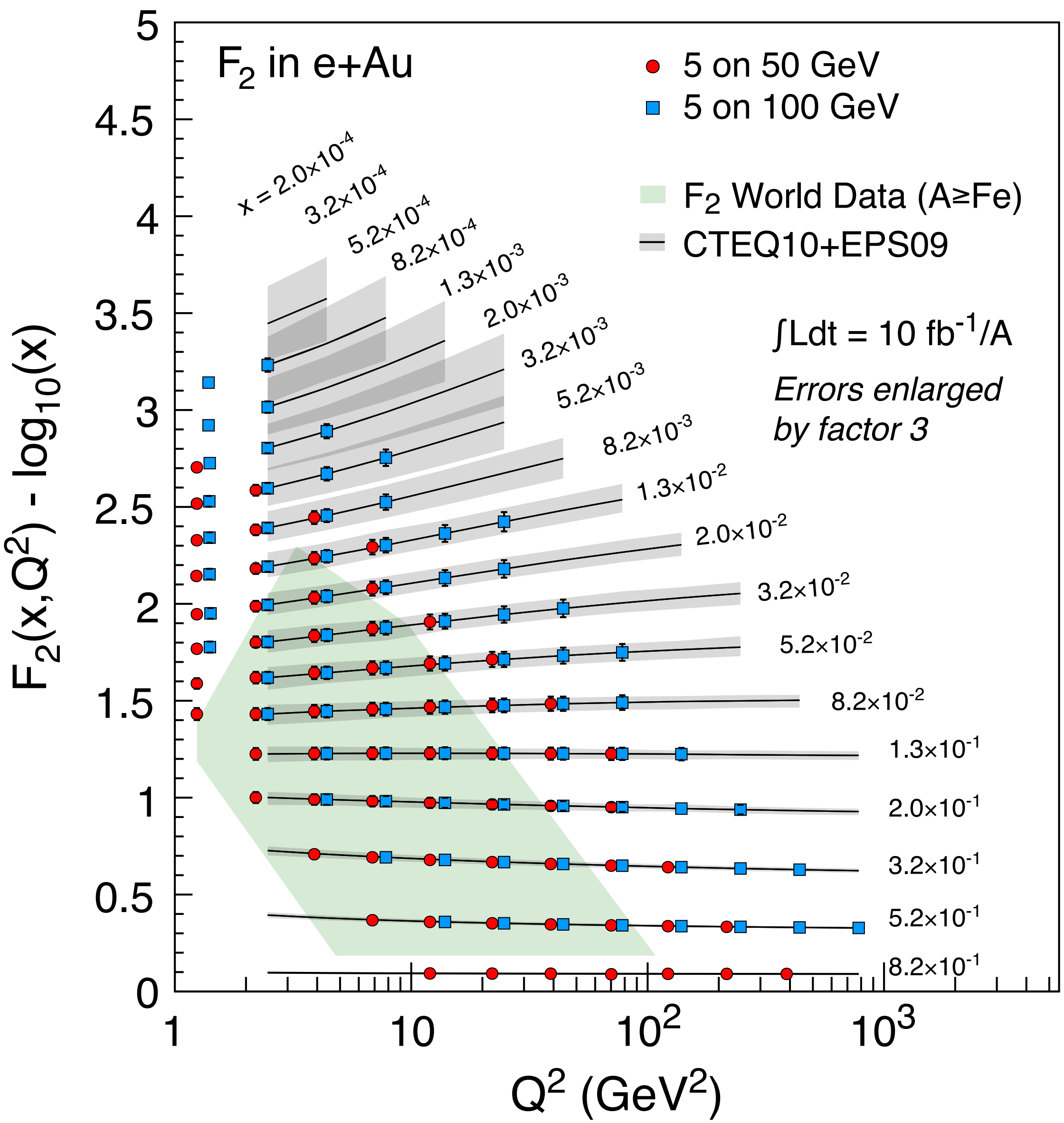

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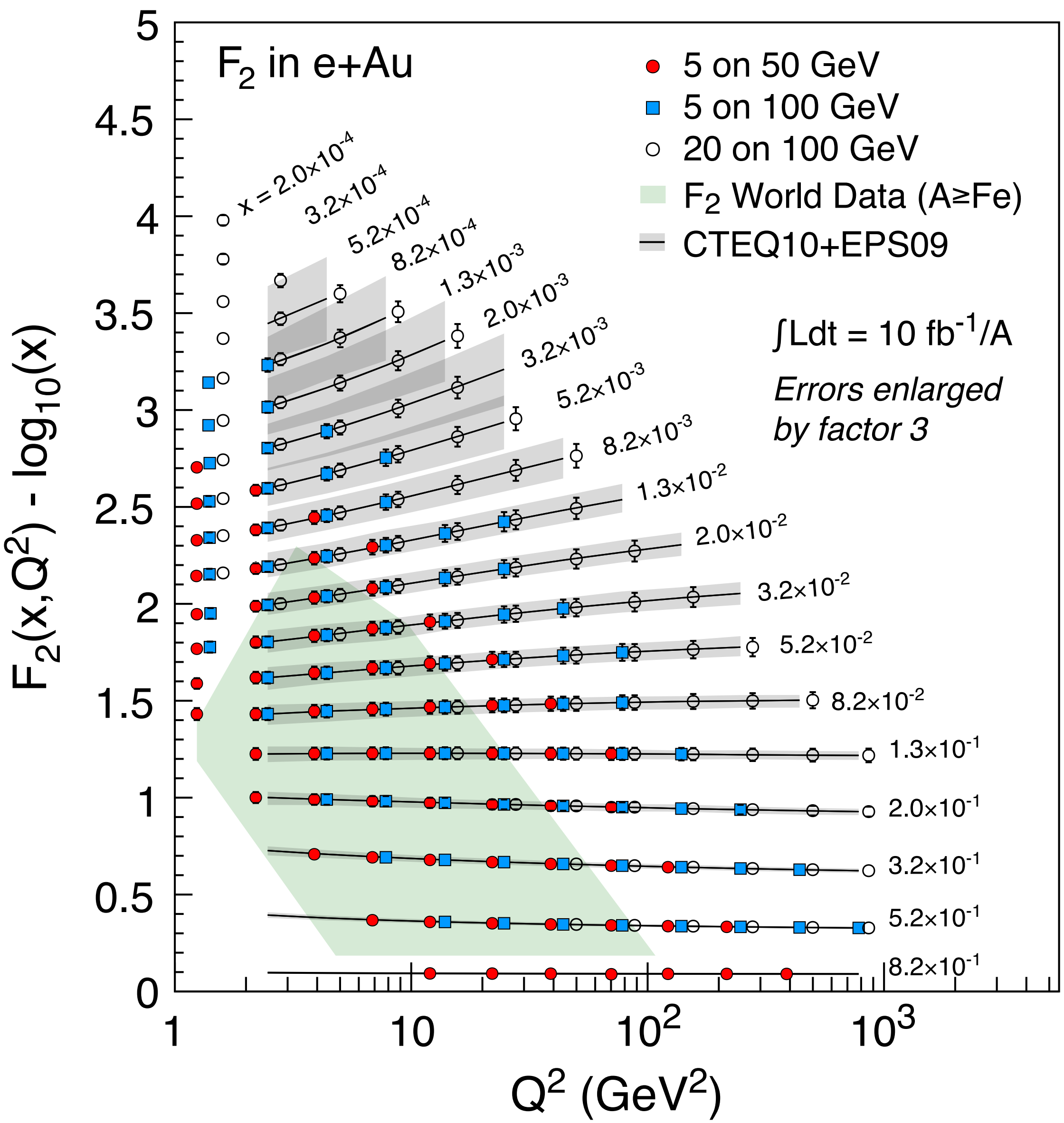

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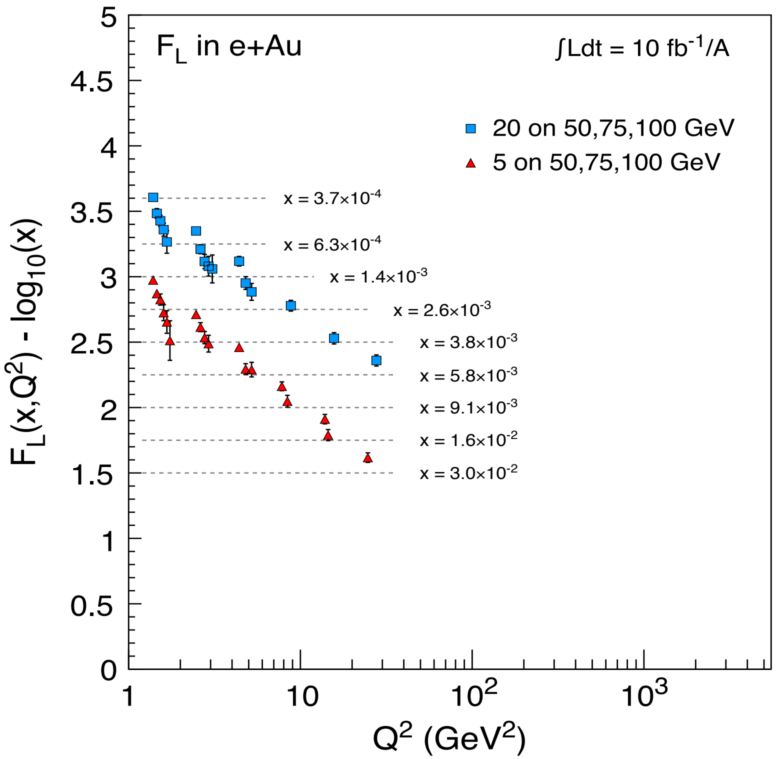
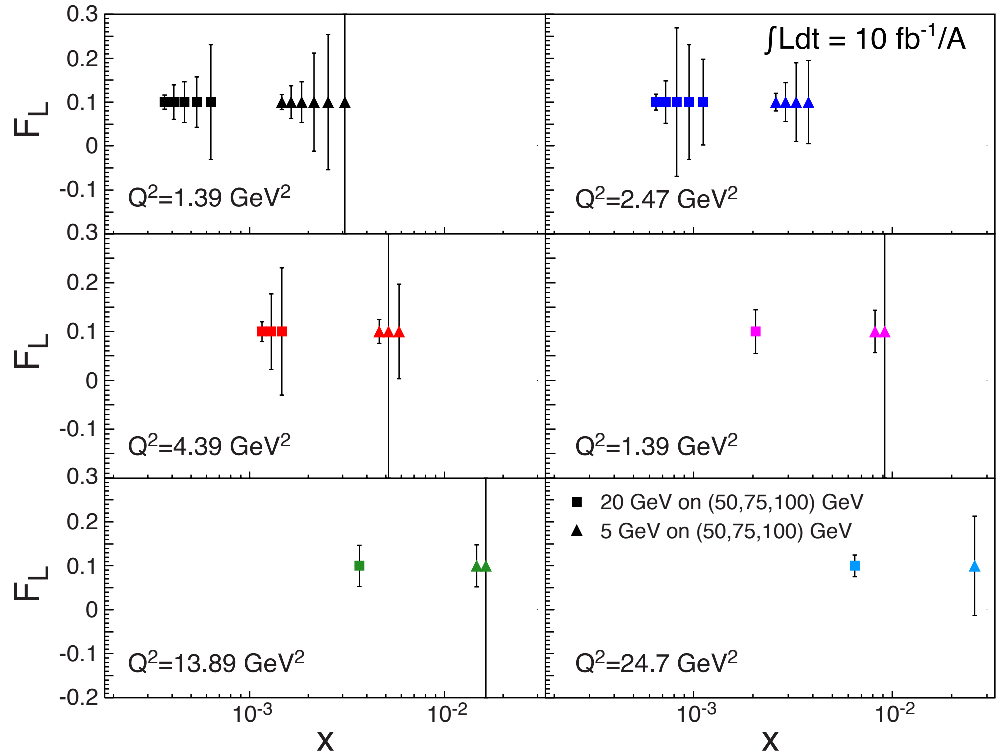
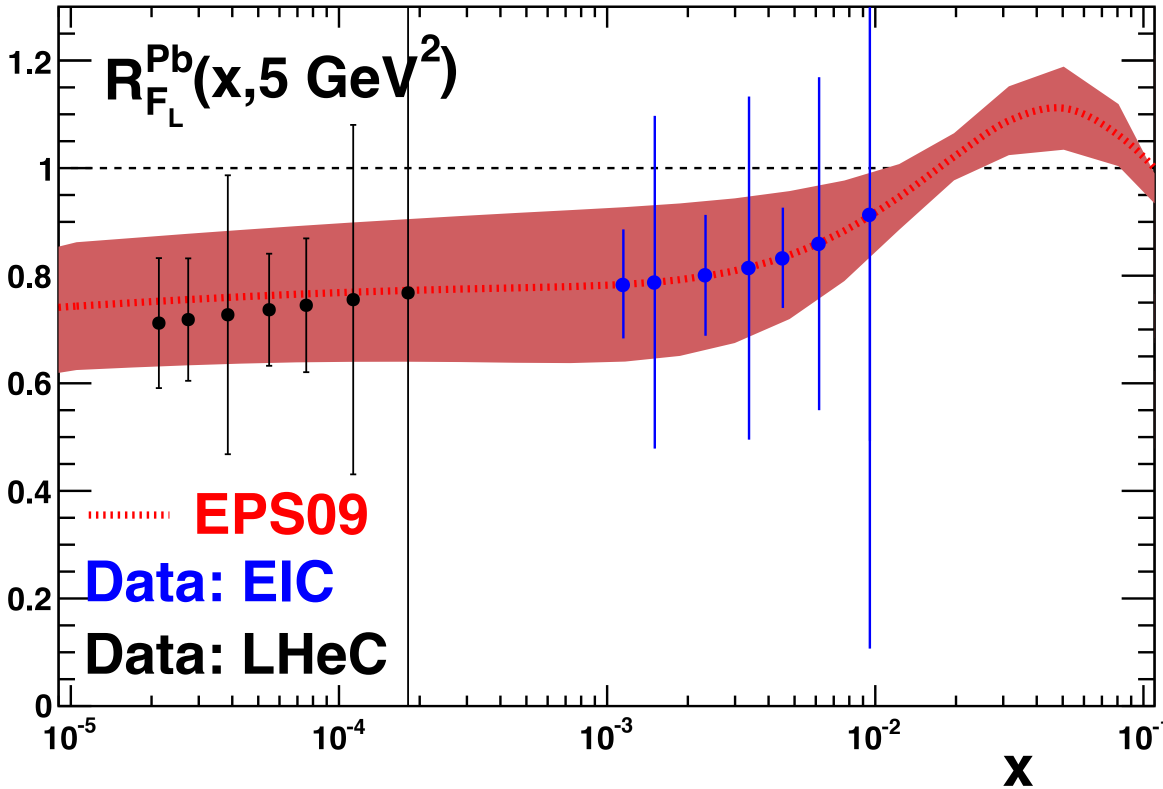
F_L Structure Function in e+A





- The measurement of F_L is more complex and more limited
  - Much larger uncertainties and much smaller acceptance than F_2 measurement
  - Require data from at least 3 different energies in each x,Q^2 bin
  - Used Rosenbluth Separation technique to extract F_L
  - Systematic uncertainty (3%) is dominating

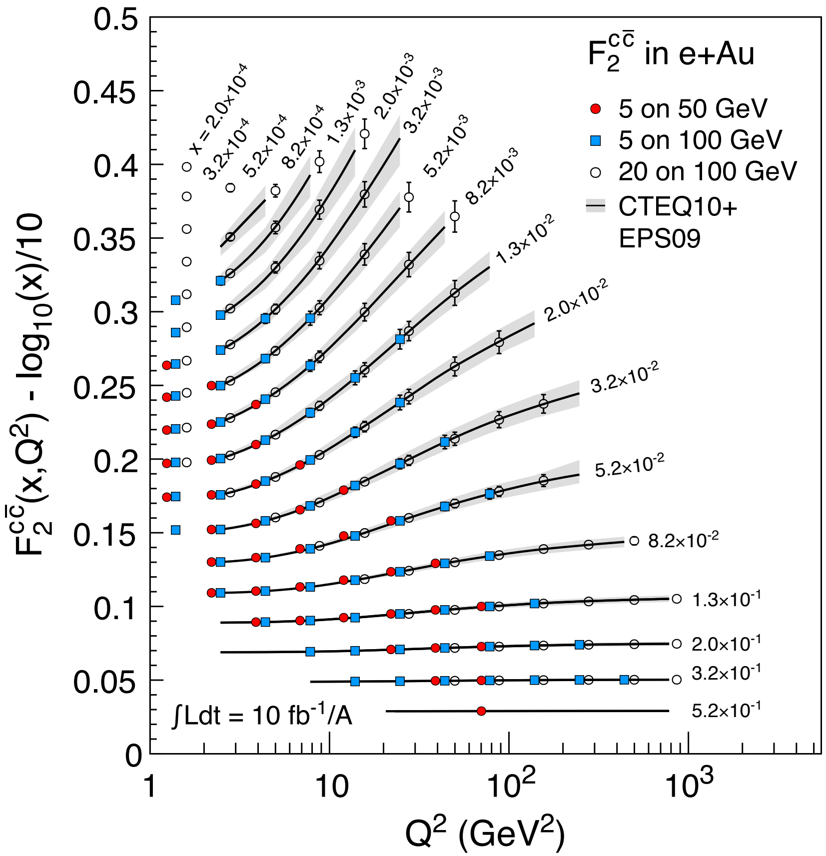
F_L in e+A: LHeC vs. EIC



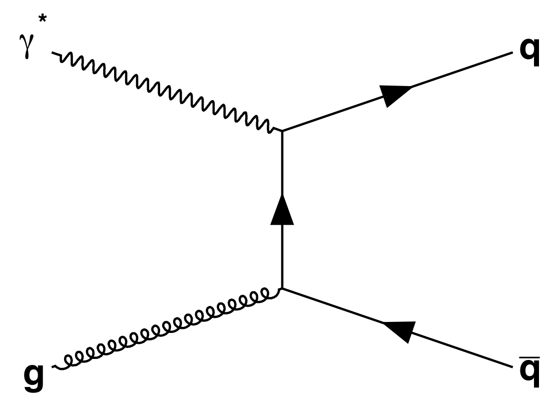
Plot taken from LHeC CDR, courtesy of N. Armesto

- Good complementarity with F_L measurement at LHeC
- Both measurements are limited by their uncertainties and σ_r appears to be the more obvious way to constrain the nuclear PDFs

EIC - $F_2^{c,A}$ Structure Function



$F_{2,c}$ driven by photon-gluon fusion (PGF)



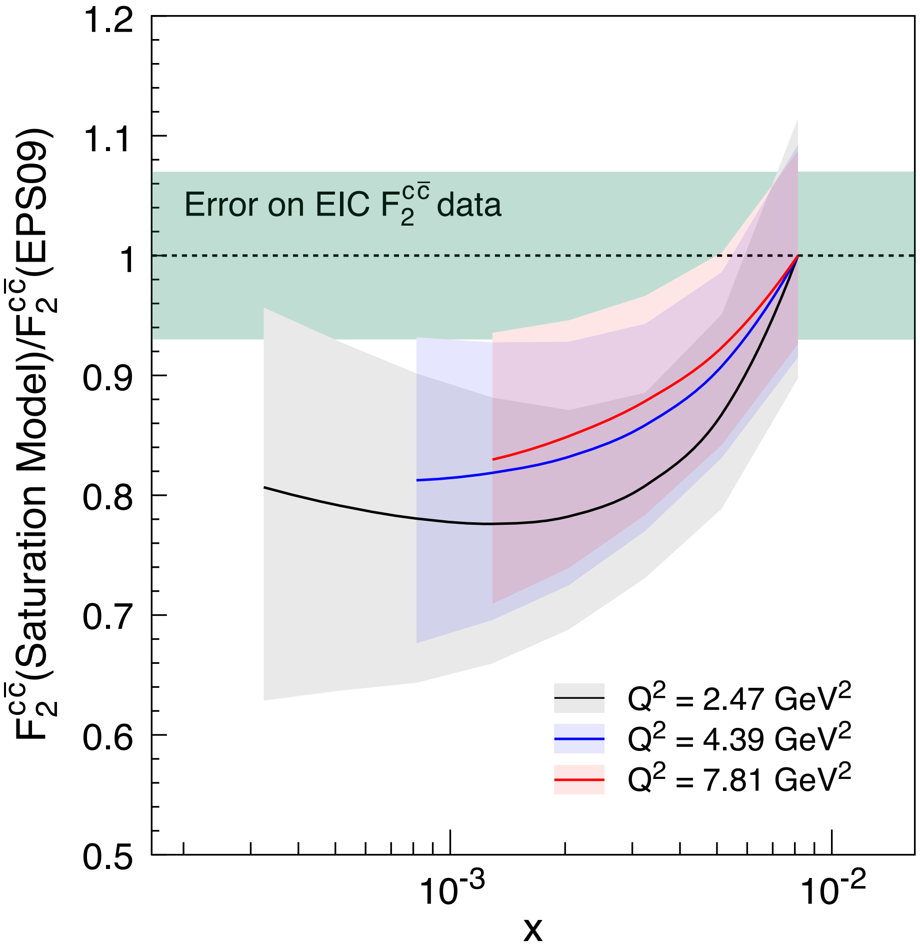
Like F_L directly sensitive to glue

F_2^c probes PDFs at somewhat higher value of Bjorken x

$$x_{\text{probe}} = x\left(1 + \frac{4m_c^2}{Q^2}\right)$$

- As F_L is a difficult measurement, F_{2c} may be the way forward
- Larger uncertainties than F_2 but smaller than F_L
- Statistics are not an issue but requires Si detectors
- At low x, uncertainties are smaller than EPS09

Can $F_2^{c,A}$ Signal Gluon Saturation?



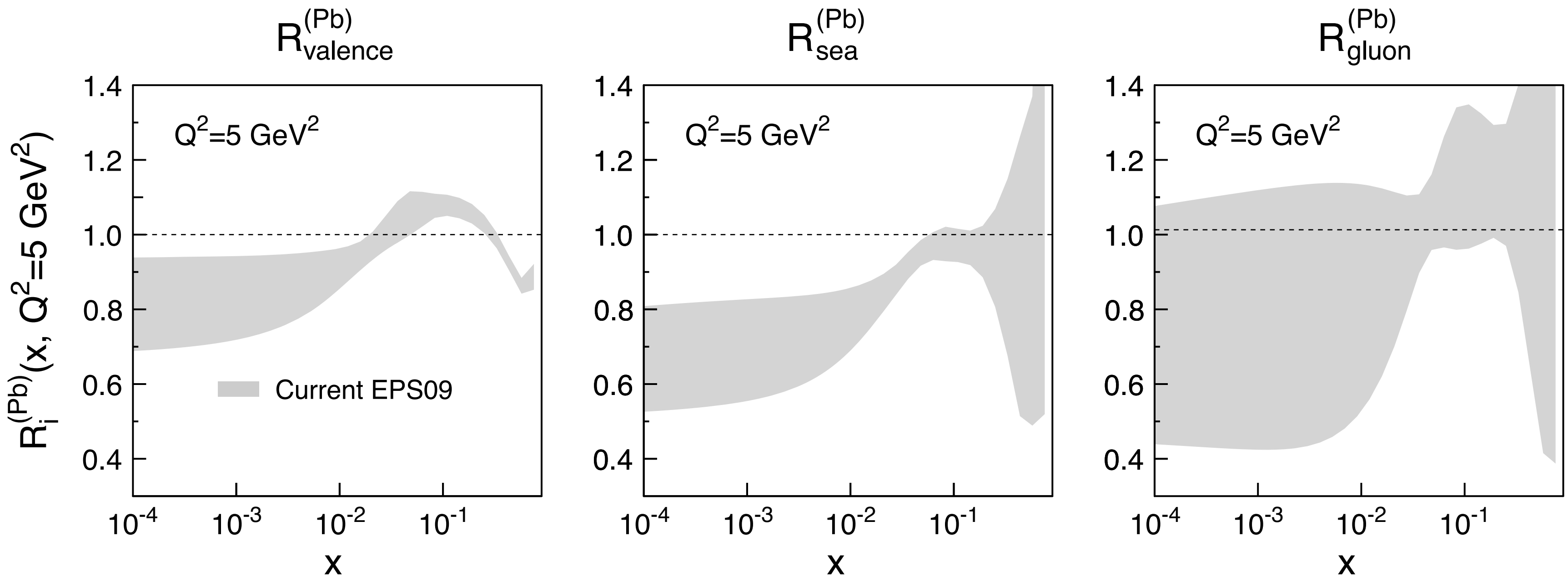
- Can potentially provide access to differences between models

  Example:

  Ratio of rcBK to EPS09 shows the possible discriminatory power of this measurement

- $F_2^{c,A}$ suffers from limited x-range, high √s required

Impact of EIC on nPDF (here EPS09)



- Ratio of PDF(Pb)/PDF(p)
  - Without EIC, large uncertainties for sea quarks and gluons
  - Adding in EIC, pseudo-data significantly reduces the uncertainties, particularly at small-x (global fit by H.Paukkunen)
  - Fitting the charm pseudo-data has a dramatic effect at high-x
  - Shed light on A dependence (here Carbon)

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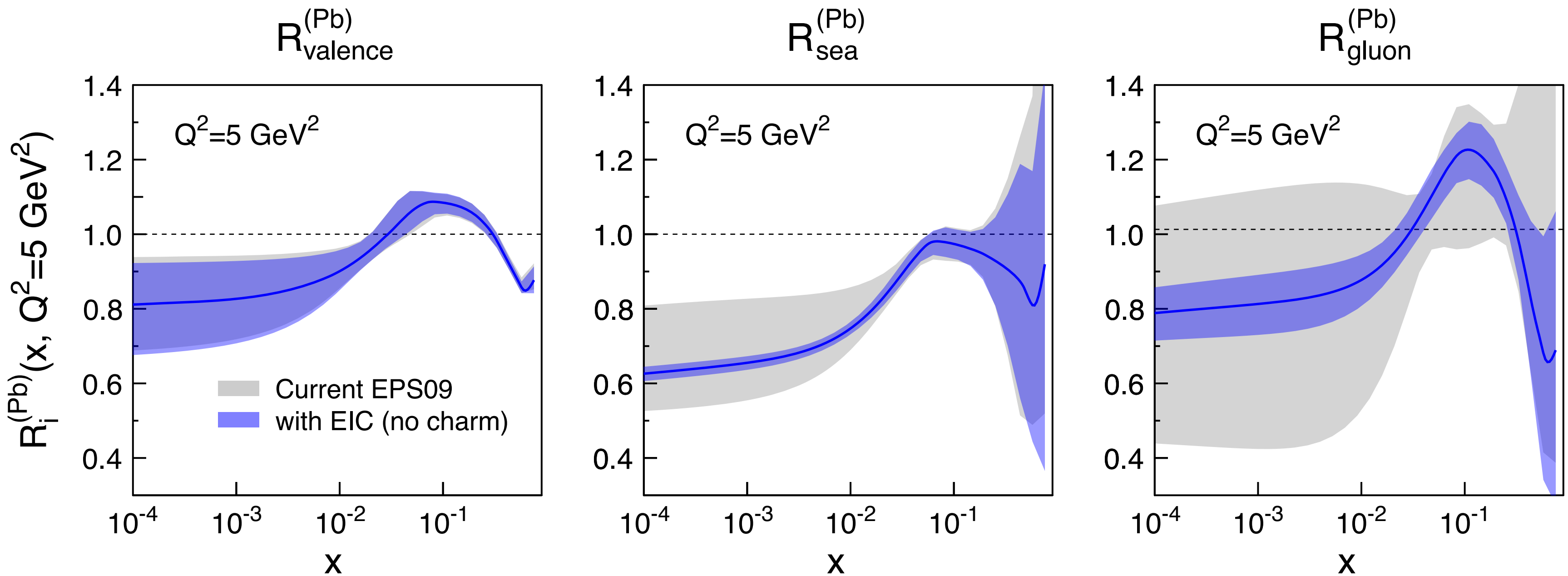

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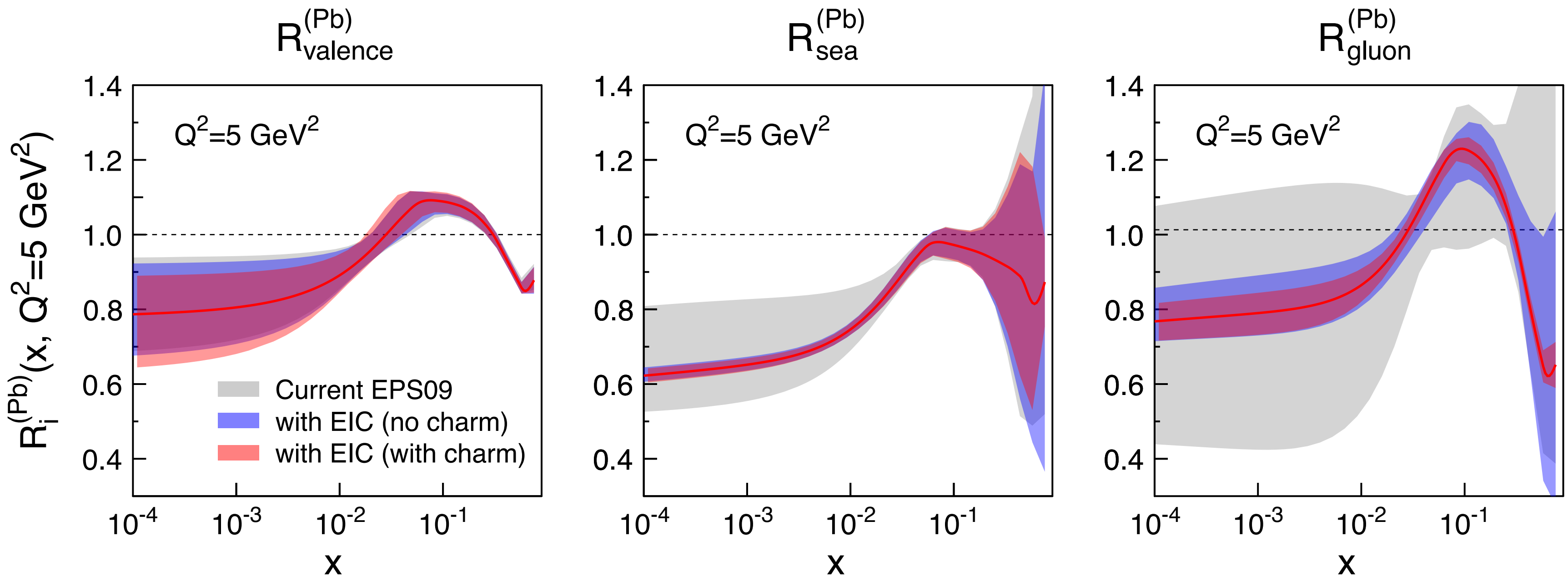

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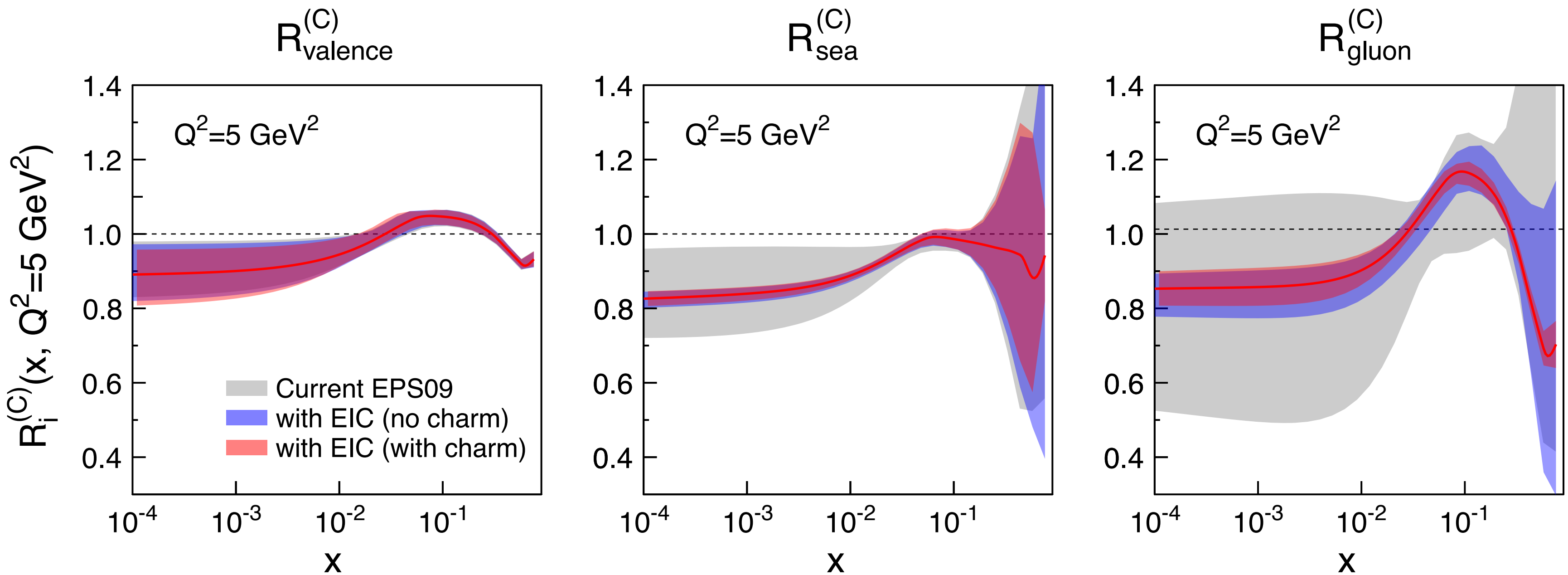

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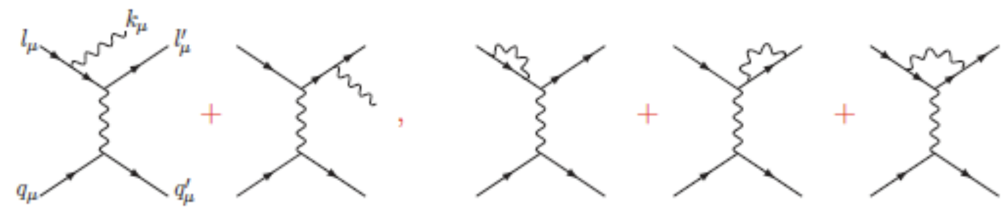
Elephant in the Glass House

Radiative "Correction"

- Emission of real photons experimentally often not distinguished from non-radiative processes: soft photons, collinear photons
- Studies underway (ignored in EIC WP)

Feynman diagrams for leptonic radiation at $O(\alpha)$ (NC)

for *eq* scattering:



$$F_n^{\mathrm{obs}}(x, Q^2) = \int \mathrm{d}\tilde{x}\mathrm{d}\tilde{Q}^2 R_n(x, Q^2; \tilde{x}, \tilde{Q}^2) F_n^{\mathrm{true}}(\tilde{x}, \tilde{Q}^2)$$

- Expect strong dependence on experimental prescriptions for measuring kinematic variables
  - leptonic variables: measure E and θ of scattered lepton ⇒ x and Q^2
  - hadronic variables: measure E, θ from hadronic final state ⇒ $\tilde{x}$ and $\tilde{Q}^2$
  - mixed variables: combine information from leptonic and hadronic final state
- Need MC to unfold, kinematic cuts can limit effect
- Detect radiated photon?

Elephant in the Glass House

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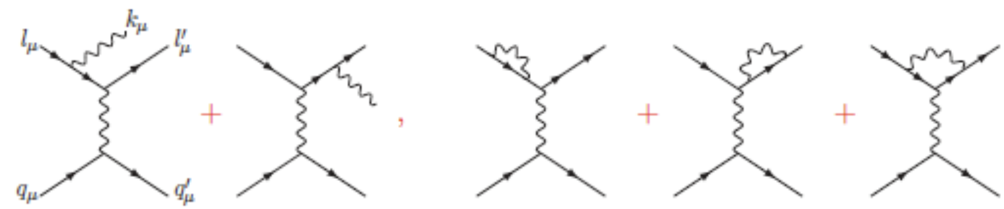
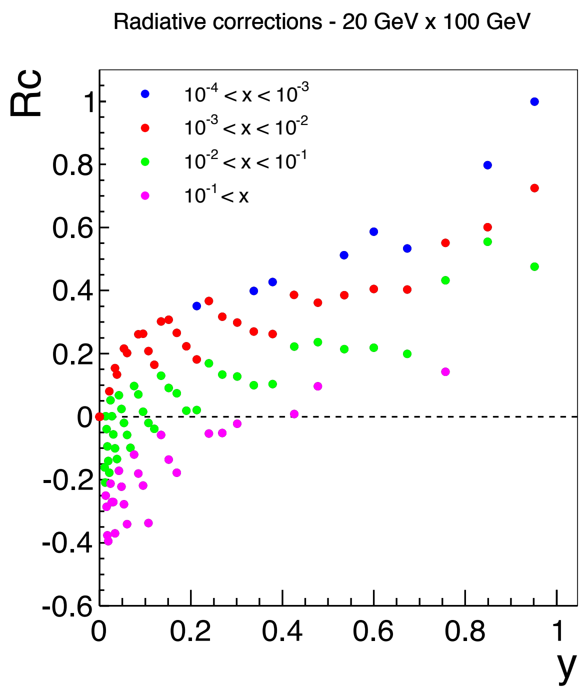
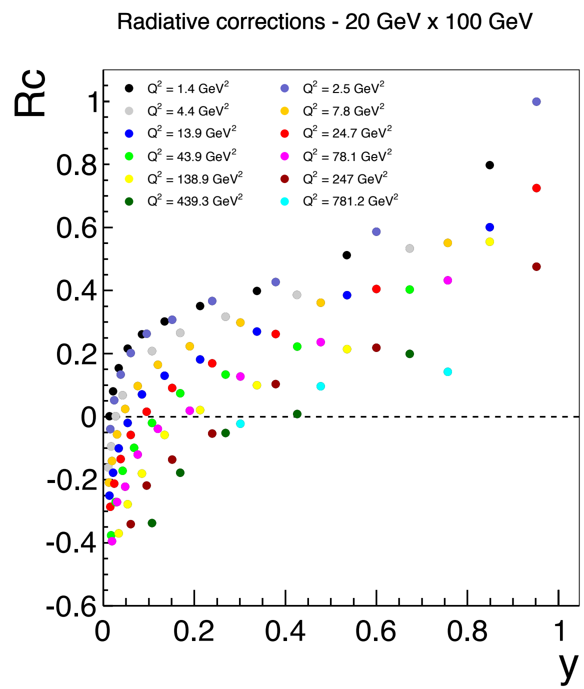


$$F_n^{\mathrm{obs}}(x, Q^2) = \int \mathrm{d}\tilde{x}\mathrm{d}\tilde{Q}^2 R_n(x, Q^2; \tilde{x}, \tilde{Q}^2) F_n^{\mathrm{true}}(\tilde{x}, \tilde{Q}^2)$$

$$Rcorr = \frac{\sigma_{red}\left(O(\alpha)\right)}{\sigma_{red}\left(born\right)} - 1$$



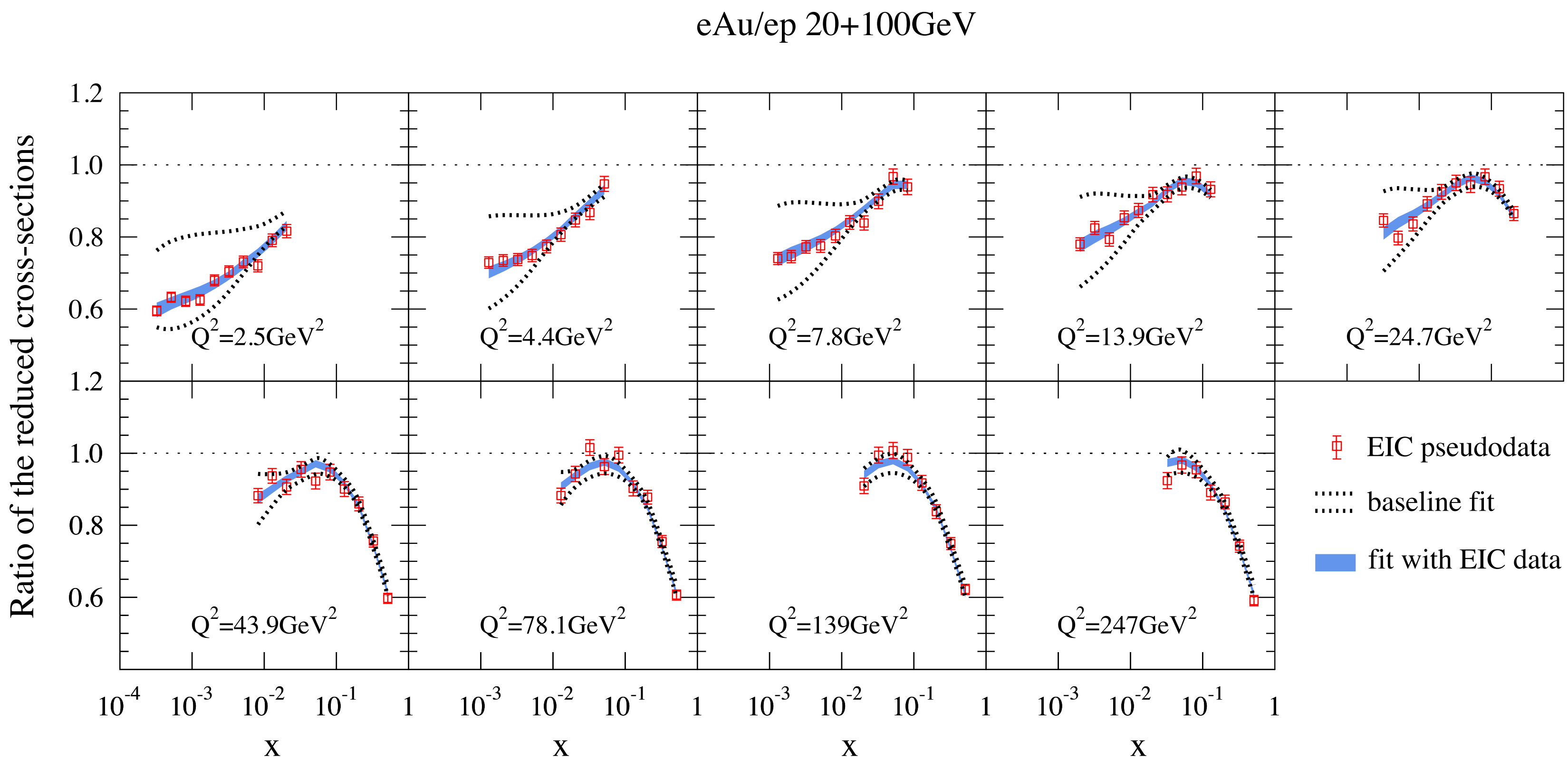


Take Away Message

- Constraints on nPDF without an eA collider are weak and uncertain
- Complete and detailed studies of an EICs capability to measure F^A_2, F^A_L, $F^A_{2,c}$ are done
- Missing piece is the study of radiative corrections (in progress)
- In eA, structure functions are sensitive to gluon saturation
- Measurement of the reduced cross-section at an EIC does substantially constraint the gluon and sea nPDFs
- $F^A_{2,c}$ does constrain nPDFs at larger x (EMC effect range)
- Quality of structure function measurements is dominated by systematic uncertainties and less affected my statistics

Supporting Material

Effect of EIC on EPS09



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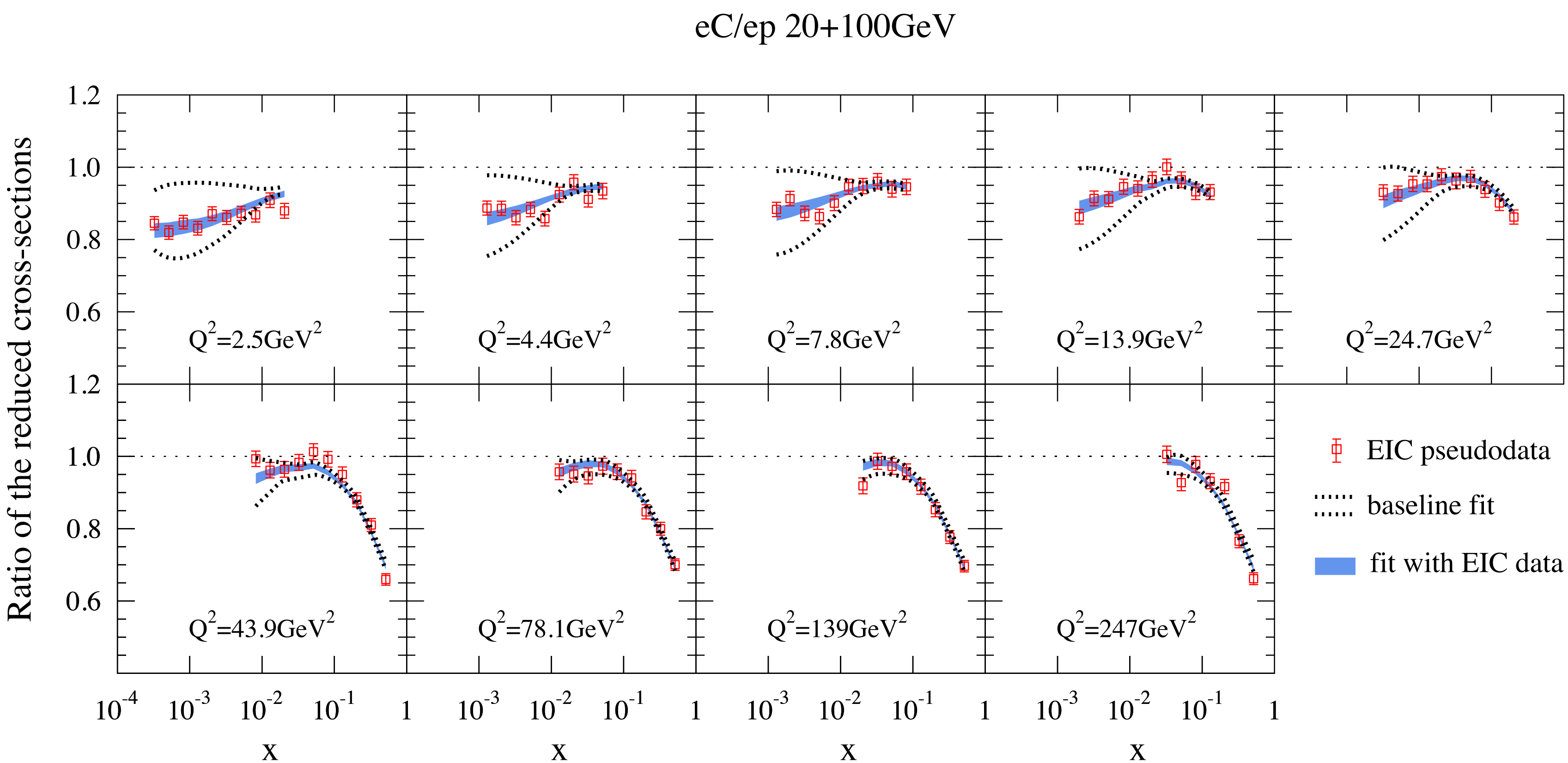

FL - Rosenbluth Separation

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y+} F_L^A(x, Q^2)$$

$Q^2 = 1.389\ \mathrm{GeV}^2$